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SHORT COMMUNICATION

The Susceptibility of Communication Satellites to the Nuclear Electromagnetic Pulse

Tawfik A. Al-Kusayer
College of Engineering, King Saud University, P.O. Box 800, Riyadh 11421, Saudi Arabia
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Abstract. The High Altitude Brust (HAB) of a nuclear weapon can produce an Electromagnetic Pulse (EMP) that rises very rapidly (in nanoseconds) to a high voltage (tens of kilovolts per meter). This pulse covers 0 to 100 MHz bandwith or frequency. The radiated EMP can affect a large portion of space with a diameter of several thousands of kilometers and produce a current transient large enough to cause permanent irreversible degradation of components and systems.

Communication satellites as exoatmospheric vehicles can be exposed to immediate gamma and x-radiation directly from the Nuclear weapon to cause System-Generated EMP (SGEMP) Transient Radiation Effect on Electronics (TREE) or Dispersed EMP (DEMP).

The open-circuit voltage developed in the internal conductors of the ARABSAT spacecraft; has been calculated as a simple example. Some recommendations have been suggested at the end of this paper.

Introduction

The primary effects of a nuclear explosion blast, heat, and radiation are accompanied by other effects caused by these primary effects interacting with the environment. A nuclear burst whether near the surface of the earth in the lower atmosphere or above the atmosphere, produces an electromagnetic pulse (EMP). This pulse is characterized by an electromagnetic field that can rise very rapidly reaching a peak in a few nanoseconds, then tailing off in a few microseconds with a high peak electric-field intensity (tens of kilovolts per meter) [1-4] as shown in Fig. 1. As a result of this sharply rising waveform, the spectrum of the EMP is spread over an extemely wide band of frequencies with its main energy within 0 to 100 megahertz [7-8], as is shown in Fig. 2. Unlike other natural or man-made sources of electromagnetic energy, a nuclear burst can radiate significant EMP fields over a large portion of the earth's surface (several thousands of kilometers in diameter) [9].

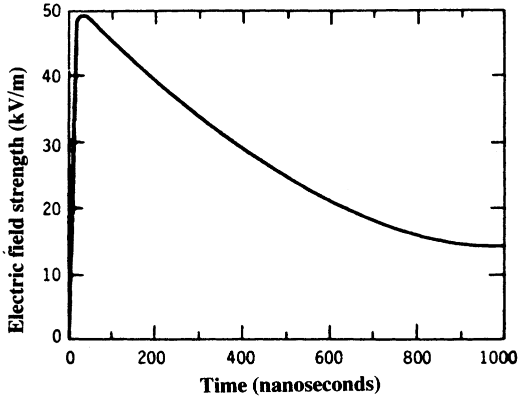

Fig. 1. The typical shape of the electromagnetic pulse (EMP) [5].

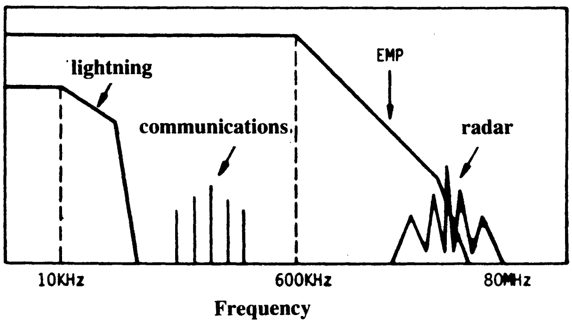

Fig. 2. The wave from spectrum of the EMP [6].

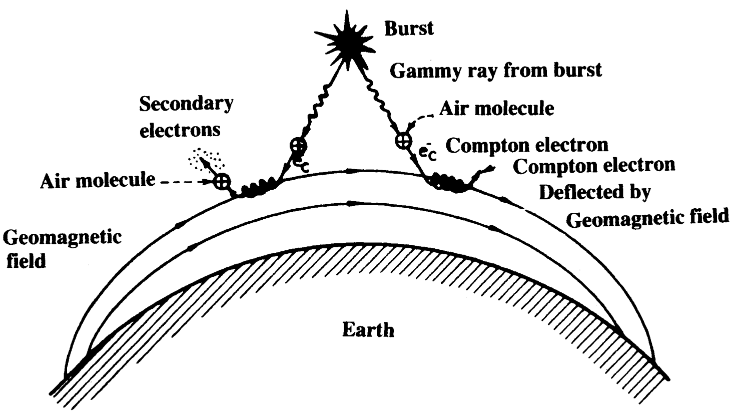

Fig. 3. EMP generation from the high altitude burst [9]

The primary source of EMP is the compton current created when high-energy gamma rays from the burst collide with air molecules and other materials. This produces high energy electrons which move rapidly away from the burst as is schematically shown in Fig. 3, for a high-altitude burst where the electrons moving under the influence of the geomagnetic field of the earth.

For the purposes of this paper it is sufficient to say that, EMP can cause large voltage and current transients, that result in serious responses in electronic systems. These responses are broadly divided into two effects, upset and damage. Upset is a nonpermanent response which results in the degradation of system functional capabilities. Damage is a permanent irreversible degradation of component or system functional capabilities.

In general, active components are more susceptible to EMP degradation than passive components, and semiconductors are more susceptible than vacuum tubes or electromechanical devices. Susceptibility thresholds also tend to vary directly with system operating levels and inversely with the complexity of the system. Modern avionics systems, with their increased reliance on electronic subsystems and a wider use of the newest technologies in semiconductor and integrated circuit design, present a potentially serious risk of susceptibility to EMP degradation [10,11].

In this work as it is dealing with communication satellites, consideration is restricted to the High-Altitude Burst (HAB), where a nuclear burst is assumed to occur above the atmosphere at altitudes of 100 kilometers or greater. In this case, the prompt gamma and X-radiation outputs are the most important radiation sources since these radiations will penetrate farthest into the atmosphere. The downgoing gammas, will begin to interact appreciably with the air at altitudes between 40 and 20 kilometers creating a compton current in this EMP source region.

The ARABSAT satellites are at an altitude of 36,000 km over the equator (the communication satellites are always on fixed altitudes over the equator, and not like military or surveying satellites that are rotating in elliptic orbits around the eath). So, according to the above discussion, the flux of gamma and x-radiation produced by the nuclear detonation will be, perhaps, more important than the dispersed EMP (DEMP) wave incident on the satellite. Since there may be little intervening media between the nuclear weapon and the satellite for a HAB directly illuminating the satellite there is little attenuation of the radiation propagation toward the satellite. The flux of gamma and x-radiation can interact with the satellite structure and components to cause system-generated EMP (SGEMP) and transient radiation effect on electronics (TREE). These effects are often more severe than the DEMP itself on satellites. In the rest of this paper the discussion will be limited to the satellite-EMP interaction only.

The high peak electric-field intensity generated from an explosion of 10 megaton Nuclear Weapon at high altitude can be calculated as follows. The total energy yield is 4.2×10^{16} Joules. The prompt gamma yield assuming at least 0.1% efficiency is 4.2×10^{13} Joules [12]. This gamma energy moves out in a thin shell, with surface density E′, where

$$E' = \frac{4.2 \times 10^{13}}{4\pi L^2} \text{ Joules/m}^2$$

where

L = distance from source burst in meters

This gamma energy is converted into electromagnetic energy in the source region at an altitude of 20-40 km. Assume 10% conversion efficiency, and the burst height is 100 km ($L = 10^5$ meters),

$$E' = \frac{4.2 \times 10^{13} \times 0.1}{4\pi \times 10^{10}} = 33.4 \text{ Joules/m}^2$$

The electric power in the field is a function of the rate at which the energy is expanded. But the average duration of the EMP pulse is approximately 500 μ sec. So, the power density P is

$$P = \frac{E'}{t} = \frac{33.4}{500 \times 10^{-9}} = 66.8 \times 10^6 \text{ watt/m}^2$$

and the electric field intensity that is generated from a detonation of 10 megatons Nuclear Weapon is

$$E = \sqrt{377 \times 66.8 \times 10^6} = 159 \text{ kV/m}$$

where 377 is the impedance of free space in ohms.

The most important part of the satellite-EMP interaction analysis is to evaluate the voltage and current induced on the satellite internal cables by the EMP. One source of cable voltages and currents arises from the direct excitation of external wiring and antennas. The antennas pick up energy from the EMP and inject it directly into the cables. The solar panels of the satellites are acting like antennas. A second source of cable excitation arises from the penetration of the EMP fields through the open apertures on the satellite skin (surface). These fields then interact with the cable in the satellites interior.

The skin of the ARABSAT satellite can shield most of the energy of the EMP from the satellite's interior as shown in Fig. 4. Some EMP energy can penetrate through the skin by the antennas and the apertures. These apertures include the horizontal slots at the connections of the C-BAND transmit and receive antennas with their platforms, the vertical slots at the joints of adjacent solar arrays the circular hole for the 490N-main Thruster, and the S-BAND antenna and IR earth sensors. These apertures are schematically illustrated in Fig. 5.

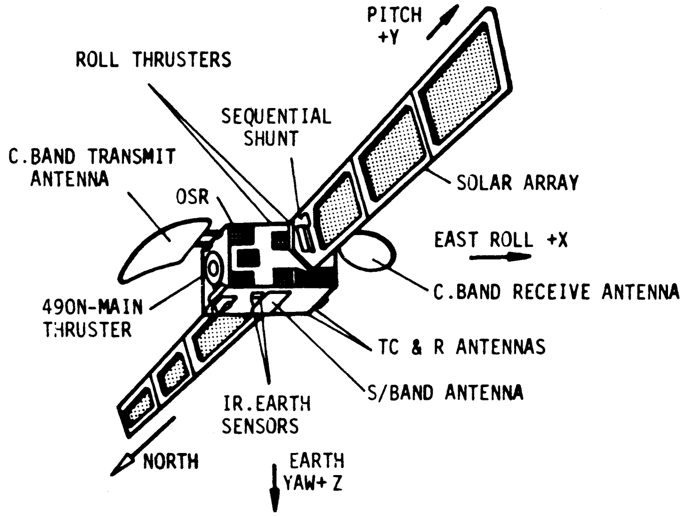

Fig. 4. Some basic features of the ARABSAT satellite [13].

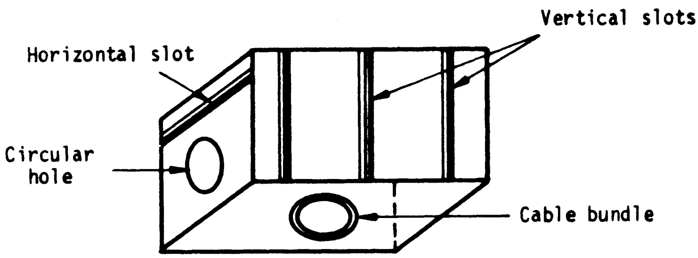

Fig. 5. A schematical model to calculate the EMP penetration through the satellite

Although, the EMP problem is only part of the satellite interaction problem involving SGEMP and TREE considerations, a simple numerical solution will be attempted below, to calculate the maximum open-circuit voltage that can be developed between the satellite shield and the internal conductors of the cable inside the satellite body.

When the satellite is illuminated by an incident EMP whose magnetic field is parallel to the satellite axis, significant magnetic-field penetration into the interior can occur via the slots and the hole as it is shown schematically in Fig. 5. It will be assumed that, all of the magnetic flux which penetrates the satellite through the slots and hole also links the cable loop. The electromotive force associated with the rate of change of magnetic flux will cause a total current I_t to flow in the cable loop, this total current will then induce currents and voltages on the internal conductors of the cable. The open-circuit voltage is estimated by treating all the internal conductors as a single conductor and by ignoring the presence of all the equipments inside the satellite.

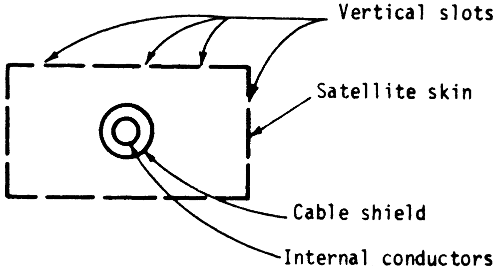

Fig. 6. Elementary satellite system topology

The system topology for this elementary problem can be schematically shown in Fig. 6. The first principal shield is the outer skin of the satellite. The penetrations of this shield to be considered in this example calculation are the vertical slot apertures in the satellite outer surface. The second principal shield is the shield of the cable bundle. This shield is typically an aluminum film, penetration through which occurs via diffusion.

The maximum open-circuit voltage V_{oc} which can be developed between the shield and the internal conductors of the cable bundle is found to be:

$$V_{oc} = 2\pi R Z_T I_t \tag{1}$$

The loop current of the cable, can be calculated as [14]:

$$I_t = \frac{-n\pi l^2 H}{16R \ln(4l/w) \ln(8R/r)} \tag{2}$$

and the transfer impedance of the cable shield [15]:

$$Z_T = \frac{1}{2\pi r \ d\sigma} \tag{3}$$

where

l = length of vertical slots, m
w = width of vertical slots, cm
d = shield thickness, mm
R = radius of cable loop, m
r = radius of cable bundle, cm
n = number of vertical slots
σ = shield conductivity, s/m
Z_T = transfer impedance per unit length of cable shield, ohm/m
H = magnetic field strengh, Amp/m

Substitute both equations (2) and (3) in equation (1) to obtain the open-circuit voltage as:

$$V_{oc} = \frac{-n\pi l^2 H}{16r\, d\sigma \ln(4l/w)\ln(8R/r)} \quad (4)$$

For the purposes of numerical illustration, using the available data about ARABSAT let l = 1.64 m, w = 0.5 cm, n = 8, R = 0.6 m, r = 1 cm, $\sigma = 3.7 \times 10^7$ s/m, d = 0.025 mm and H = 399 (corresponds to a peak electric field strength of 150 kV/m, below the ionosphere). Then the open-circuit voltage is given by

$$|V_0| \simeq 10.6 \text{ volts}$$

This developed voltage can produce a current transient, sufficient to result in degradation of system functional capabilities, or what is called system upset [16].

Recommendations

To minimize the induced voltage in the satellite inner connections and cables, the following suggestions are recommended:

1) To use the Fiber-optics in the electrical internal connections wherever possible.
2) To minimize the length of the solar arrays to the minimum required.
3) To reduce the number of the outside slots and holes to the minimum.
4) To use some techniques to absorb/arrest the open/close-circuit induced voltage generated in the cables and metalic parts of the satellite, due to the EMP effect.
5) To shield the equipments inside the satellite by metalic compartments connected to the common ground of the satellite body.

6) To use high and low frequency filters in the receiving antennas to eliminate the unwanted frequencies that are caused by the EMP.

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